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ABSTRACT

Following a review of recent research in the University of Washington Department of Psychology project, Individual Differences in Cognition, analyses are reported linking performance in laboratory studies of cognition to performance on selected psychometric instruments. Intent of the study was to provide an empirical followup of Carrolls's (1974) careful analysis of the information processing requirements of tests of cognitive factors. The results provide general support for Carroll's conclusions and suggest that a resolution of the long standing psychometric question of whether aptitudes or achievements are being assessed can be realized through studies designed to survey individual differences in current information processing capabilities. (Author/WR)

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Individual Differences in Memory and Information Processing

Clifford E. Lunneborg

The research I am going to discuss today is drawn from a long-term project under the direction of Earl Hunt at the University of Washington, a project we style Individual Differences in Cognition. Dr. Hunt, with an experimental background, and I, from a psychometric persuasion, undertook this work out of a conviction that it ought to be possible to establish some correspondence between measures of individual performance along dimensions implicit in modern theories of human cognition, particularly theories of memorial organization and operation, and measures of intelligence or cognitive abilities. After all, both are concerned with the processing of information. If such relations can be established they would be of interest both to the cognitive theorist and to the psychometrist. For cognitive psychology the message would be that individual differences in intelligence are well-established and need to be mirrored by individual differences in parameters postulated for any cognitive theory. For the psychometrist the expectation is that assessment of purely normative individual differences in global performance can be replaced by individual differences which can be expressed in terms of a processing metric (time, capacity, rate) required by a theory of information processing. In short, we seek either a theory of cognition that takes individual differences into account or a means of assessing individual differences with some theoretical basis.

We are working within the framework of a distributed memory model (Hunt 1971, 1973). Briefly characterized, the distributed memory model is concerned with the buffering of sensory information into central memory, recoding of information within and between memory stages, retrieval of information from memory, and the cross-referencing and comparison of information stored in memory. Human information processing is likened to a computing system with control processes manipulating information stored in a data structure subject to the constraints of the brain's system architecture. Between individuals, differences in cognitive performance can be contributed to by differential characteristics of the

physical system, by differences in availability or efficiency of control processes, or by differences in the organization of the data structure. How might differences of these kinds relate to tested differences, for example, in verbal intelligence or spatial ability?

Review

Although our earlier work is described in greater detail elsewhere it may be helpful to briefly review it before describing any new results. In our first series of studies (Hunt, Frost, and Lunneborg, 1973) a number of experimental paradigms important to the development of the distributed memory model were replicated with tested psychometric intelligence included as an independent variable. For these studies subjects were recruited from among university freshmen who as high school juniors had taken a test battery of ten intelligence related measures. Only two of these psychometric scores, however, were employed: Verbal Ability, a composite score from four separate verbal subtests, and Quantitative Ability, a composite score from five numeric subtests. These two were selected because of the widespread acceptance of such assessments as two of the most important aspects of intelligence as presently measured. Freshmen were recruited who had extreme scores within the range of the University undergraduate population forming four groups, low verbal-low quantitative, low verbal-high quantitative, high verbal-low quantitative, and high verbal-high quantitative. Low and high were defined as within the bottom or top quartile of University scores.

The experiments selected for replication dealt either with short-term memory (STM), which holds stimulus-bound codes for a period of seconds, or with intermediate-term memory (ITM) which holds a semantic code for a period of several minutes to perhaps an hour. An overview of results of those experiments suggested two consistent, intelligence-related findings.

1. <u>High verbal ability is associated with greater efficiency of short-term memory</u>. (A) High and low verbal subjects were tested using the varied set procedure of the Sternberg (1970) paradigm. From one to five digits, a memory set, were displayed simultaneously for three seconds.

Two seconds later a probe digit appeared. Subjects were asked to report whether the probe was in the memory set or not. Response latencies were determined and high verbal subjects were determined to have significantly faster search rates than low verbal subjects. High and low quantitative subjects did not differ.

(B) In the Posner matching task (Posner and Boies, 1971) subjects looked at a letter followed, with an interstimulus interval of zero seconds, by a second letter. Under one condition, the physical match condition, the subject responded "same" if the two letters were physically the same (e.g., AA), while in the name match condition the subject responded "same" if the two letters had the same name (e.g., A and aA). Analysis of latency of response results suggested the high verbals had faster access to names than low verbals. No difference was obtained for the physical matching task nor were the high and low quantitative groups differentiable.

(C) Two other studies, suggested by the findings of Wickens (1970) with proactive inhibition and Puff (1966) with semantic clustering, had the following results: high verbals were more effective in holding onto the temporal order of elements in short-term memory, and secondly, in recalling a randomized list of categorizable names (animal, vegetable, mineral names), low verbals clustered while high verbals recalled the items more in order of presentation.

2. <u>High quantitative ability is associated with greater resistance to loss of information through interference</u>. (A) In the Atkinson and Shiffrin (1968, 1971) continuous paired associates task subjects are asked to keep track of the changing association between each of a small set of fixed stimuli (four consonant-vowel-consonant trigrams in our replication) and responses randomly selected from a large set (here digit pairs between 01 and 75). Extreme verbal-quantitative groups were administered 150 trials following initial pairing of trigrams and digit pairs. In each trial subjects were asked to respond to one of the selected trigrams with the associated digit pair and that trigram was then assigned a new numeric association. Lags between pairing and subsequent recall varied from 1 to 14 intervening trials. Analysis of correct and error

responses over the several lags permitted the estimation of four memory parameters for each subject: probability that an item will enter short-term memory; number of items that may be held in short-term memory at one time; rate of transfer of information from short-term to intermediate-term memory; rate at which information becomes unavailable from intermediate term memory. The first three parameters are considered to be affected by the subject's choice of strategy for handling the experimental task. The measure of effective loss of information from intermediate-term memory, on the other hand, is presumably a measure of the extent to which one is distracted by incoming information after an item has been fixed in memory and, as such, may be less under the subject's control. It was this last parameter that was related most strongly to the intelligence score groupings. Rate of loss of retrievable information from memory was reliably lower for subjects in the high quantitative groups.

(B) Similarly, in a replication of the Brown-Peterson paradigm (Peterson and Peterson, 1959), high quantitative Ss were consistently better in recall following a distracting task. And, in an analysis of our colleague Tom Nelson's long-term memory (LTM) data (Nelson, 1973), while verbal ability predicted rate of learning, quantitative ability predicted retention over 5 weeks of paired-associates.

In our second series of studies (Hunt, Lunneborg and Lewis, 1974) we sought to explore a little more thoroughly the finding that high verbals appeared to manipulate information in short-term memory more rapidly than low verbals. These studies were again conducted by recruiting and paying two groups of University freshmen, one group whose high school test scores placed them in the top quarter of University freshmen in verbal ability and a second group whose scores placed them in the bottom quartile. These high and low verbals participated in six experiments which I will briefly characterize under three hypotheses.

1. High verbal ability is associated with greater speed of access to overlearned codes. This hypothesis was suggested by the results obtained on the Posner task in the first series of experiments and that task was repeated in two versions. In one the stimulus materials were

presented by computer display, and in the second, Ss sorted cards bearing pairs of letters. The same 20 high and 20 low verbals were in both studies. In both instances an analysis of variance revealed a significant interaction between name vs. physical match with verbal ability--high verbals had a decided advantage under the name identical conditions.

The third study under this hypothesis had eight high and eight low verbals recall, following a short interpolated task, lists of letter clusters which had been exposed a cluster at a time. Embedded in certain of the lists were adjacent letter clusters which would make up a word. The basic finding was that while there was no difference between high and low verbals in the recall of clusters which did not form words, high verbals were significantly better than low verbals in the recall of word-forming clusters. High verbals were able to make use of the word-forming nature of the clusters, while low verbals were not. This finding persisted when the results were corrected for differential familiarity with the words in the lists and for differential success in recalling words from word lists presented in the same experimental setting.

2. High verbal ability is associated with better retention of order information. (A) The first experiment assessed the ability to maintain order information in STM in a situation in which semantic content was not a variable. A variation of the well-known Peterson and Peterson (1959) technique was used. Four letters were shown in sequence on a computer display screen followed by a variable number of digits. The subject named each character as it appeared and was then asked to recall the letters in the order in which they had been presented. Twenty-four high and 25 low verbals participated. Responses were analyzed by position within the list of recalled items and by length of the intervening string of digits. Two types of errors were identified--transposition errors (correct letter out of place) and non-transposition errors (letter reported that was not shown). Low verbals made more errors of both types than high verbals regardless of the amount of retroactively interfering material. The high verbals' advantage decreased, however, as the number of intervening digits increased.

(B) A second study by Poltrock in our laboratory used quite a different method for studying sensitivity to stimulus order, a method which requires a little explanation. Ru Day has reported that if a pair of speech sounds are presented separate o the right and left ears, right-handed Ss will be biased toward perception of the stimulus in the right ear as being the leading stimulus, even though it may have lagged the left ear stimuli by 50 milliseconds (Day, Cutting and Copeland, 1971). A similar left ear (right brain) bias has been shown for perception of the temporal order of pure tones of varying pitch. Hunt has proposed that the determination of order occurs when a recognized stimulus arrives in STM. As recognition of speech sounds should occur in the left brain speech center, a speech sound in the right ear would thus be recognized directly, whereas recognition of a speech sound presented to the left ear should require transfer of information across the cerebral commisure. This would account for the right ear bias for perception of the temporal order of speech stimuli. The extent of the bias should depend upon the speed of communication of information within the brain. In general, the faster the information transmission within the brain, the less the bias toward favoring the right ear. If high verbals are in fact capable of more rapid internal transmission of information, then they should show less of a bias in favor of the right ear.

Three groups f subjects were used including a middle verbal group, 16 Ss in each group. High verbals were indeed more accurate in the perception of speech sound order (the stops ba, da, and ga). They showed effectively no bias in favor of the right ear. However, there were no differences between the groups in judging temporal order of non-speech stimuli (buzz, hiss, tone).

3. High verbal ability is associated with more rapid processing of information in simple-problem solving tasks. (A) In the first study we used a modification of the task first proposed by Clark and Chase (1972). The subject read a simple assertion about a picture (* above + , + not above *) and then looked at a picture and reported whether the assertion was accurate or not. The times taken to read the assertion, encoding time, and to make the true-false judgment, decision time, were recorded and analyzed as a function of the complexity of the assertion and

its accuracy. Each trial can be described by stating (1) whether the sentence is true or false about the picture, (2) whether the sentence contains the unmarked preposition "above" or the marked preposition "below," and (3) whether or not the sentence contains the word "not." Other studies have suggested that "true" responses are made more rapidly than "false" responses, that the marked form of a preposition is more difficult to process, and that it takes longer to process a negation (Trabasso, 1972). An analysis of variance of data from 10 high and 10 low verbals for both decision and encoding times indicated that virtually all the variance was due to (1) the true-false distinction (decision times only), (2) the negation effect, and (3) the interaction of the negation effect with verbal ability. While the marking effect did not reach statistical significance, low verbals took almost twice as long as high verbals to process a negation. Importantly enough, this was true for decision time as well as for encoding time. High verbals continued to have an advantage even after the assertion had been read or encoded.

(B) The final experiment from our earlier series is similar to the Clark and Chase task in that it involved a problem task which can be made more complex. In this study 24 high and 25 low verbals were asked to complete a series of mental addition problems. Each problem required that the S "take in" a first term and then, when that was completed, to take in a second term and report the sum. As with the Clark and Chase task, time to encode the first term and time to report the sum were separately measured. The problems were of differential complexity along two dimensions, number base and necessity for a carry operation. Base was manipulated by asking subjects to add digits (base 10), days of the week (base 7, Monday taken as the first day), months of the year (base 12, January the first month), or letters of the English alphabet (base 26, A, the first letter). While Monday + Wednesday = Thursday does not involve a carry, November + June = May does. Although there was little difference between high and low verbals in time taken to read the first addend, high verbals had a progressively greater advantage in time taken to complete addition as the problems became more complex--carry vs. no carry in the same base or base changing from decimal to

week, to month, to alphabet. All three of the hypotheses relating to the superiority of high verbals were borne out.

Additional Work

These findings with respect to high and low verbals are very challenging if one recalls what it means operationally to be labelled high or low verbal. The four tests employed to produce the Verbal Ability score were Spelling, Vocabulary, English Usage (grammar and punctuation), and Reading (paragraph) Comprehension. While there is a speed of processing component to these, as to most psychometric measures, one is struck by the fact that for nearly all there is assumed to be something known, some specific contents in the long-term memory store, which is important. What distinguishes the high from the low verbal is, on the surface, knowing the spellings of words, meanings of words, rules by which words are put together, and knowing how to extract meaning from strings of words. Yet we have found consistent differences associated with verbal ability which are not dependent upon the contents of LTM, but largely upon rate of processing of information in STM. Why is this true? Although it is tempting to speculate that it is the high verbals' greater information-processing efficiency that permits the relevant contents of LTM to be built up more rapidly, we aren't prepared to say that is the answer. What we are prepared to say, though, is that studies like these may help unravel problems of this kind. The question of whether individual differences are due to differences in LTM contents, or to differences, say, in STM operations is an ancient and honorable question in psychometrics. In psychometric terms we worry about whether we are measuring an aptitude or an achievement. Although there is fairly general agreement that both "things" exist, the proceedings of a recent conference on the "aptitude-achievement" distinction (Green, 1974) suggest that we are far from agreement on what constitutes an appropriate measure of which construct or, indeed, whether the two constructs are measurable. Some appreciable part of the problem, we believe, is that aptitude and achievement tests have been constructed without reference to any cognitive theory. As we become more successful in designing measures keyed to our best guesses as to how man processes information, we hope that this problem will vanish.

We aren't there yet but there is growing interest in getting there. While we have taken one tack in the attempt to build bridges between the psychometric assessment of individual differences in cognition, on one hand, and models of information processing on the other, John Carroll has developed a second strategy which should be complementary and the additional results I would like to discuss today are from analyses stimulated by his work (Carroll, 1974). Th studies I have so far reported have involved taking measures suggested by a model of information processing and seeing whether psychometric types differed on those measures. What Carroll has done is to take a representative sample of psychometric tests, those assembled in the Kit of Reference Tests for Cognitive Factors (French, Ekstrom, and Price, 1963), and to examine each with respect to the same distributed memory, information-processing model we have employed. This permits him to characterize each test with respect to the demands that test makes on an information-processing system. More specifically, he identified those information-processing characteristics which would be expected to show individual differences and which would affect performance on an item in the test.

What these characterizations suggested to us was a framework within which we could look at relations between our laboratory measures of information processing and the test performance of our subjects. The study I am about to describe is the first attempt to do this. The data had been collected before we learned of Carroll's work and were also the first data obtained after we computerized part of our laboratory procedures. As a result of this latter circumstance the gremlins ate a part of our data. We don't have the data, then, we would have if we set out to design the study today. We think, however, it will serve to illustrate the approach.

Method

Subjects: Sixty-four high school age subjects from the Seattle area were recruited summer 1973 via a community Job Line. In groups of eight they spent half a day on each of two consecutive days in our laboratory. During each session they participated in several short laboratory assessments and completed a battery of short paper and pencil tests. Subjects were paid on an hourly basis for their participation.

Psychometric Instruments: The seven tests may be briefly described.

1. Verbal Comprehension, EAS test 1, calls for the subject to select a synonym from among five alternatives for each of 30 words. Five minutes are allowed to work on the task. As with the other multiple choice tests in this battery the score is the number of items answered correctly minus a fraction of those answered incorrectly. In the Reference Kit scheme this test measures Factor V, Verbal Comprehension.

2. Numerical Ability, EAS test 2. Part 1 contains 25 items of the form "16 + 18 = ____ " with the answers to be selected from five alternatives. Two minutes are allowed on this part. Part 2 consists of 25 problems of decimal fractions, for example, "1.6 x 0.3 = ____ ". Four minutes were allowed for this part. The two parts provided a single score. This test measures Factor N, Number Facility.

3. Space Visualization, EAS test 5, presents the subject with a series of ten line drawings. Each drawing depicts a stack of blocks and the subject's task is to report, by marking on an answer sheet, for each of the labelled blocks the number of other blocks in the stack that are in contact with it. Five minutes are allowed and the score is the number of correct counts completed. The test is considered a measure of Factor Vz, Visualization.

4. Numerical Reasoning, EAS test 6, presents subjects with twenty number series. The task is to select the next, eighth element from among five alternatives.

This test taps Factor I, Induction, as well as Number Facility.

5. Verbal Reasoning, EAS test 7, is a deductive reasoning test and a measure of cognitive factor Rs, Syllogistic Reasoning. Subjects are presented with a set of four facts followed by five conclusions and asked to report for each conclusion whether it is true, false, or of indeterminate validity. Six such exercises may be attempted in the five minutes testing time.

6. The Minnesota Clerical test consists of two parts each yielding a separate score. In part 1 subjects compare pairs of numbers (from 3 to 12 digits in length) and check the pairs which are the same (3 minutes). The second part of the test is identical except that the pairs consist

of names of individuals or businesses, and again, this part runs for 3 minutes. These Clerical Number and Clerical Name scores should both tap Factor P, Perceptual Speed.

7. Hidden Figures is an experimental test included in the Reference Kit as a measure of Factor Cf, Flexibility of Closure. Subjects are presented with five polygons and asked to determine for each of sixteen complex line drawings which polygon is hidden in the complex figure.

Laboratory Measures: Our "marathon" laboratory sessions involved subjects in several settings. Only those which provided measures for the present analyses, however, will be described here.

1. Motor Reaction Time was the median time taken to respond by key press to the onset of a + on a CRT screen.

2. A choice reaction time study provided a median time to respond discriminatively by depressing a left or right key to two stimuli, a circle appearing either in the left or right half of a CRT display. This choice reaction time was not itself employed in the present analysis. Rather a variable called Choice Time was defined as the difference between the median choice and motor reaction times.

3. The choice reaction time study above also provided a second variable for this analysis: proportion of trials on which the correct choice was made.

4. In the Stroop task subjects were asked first to report orally the colors in which a series of asterisks were printed and then report the color of printing of an equivalent length list of contrasting color names. The task was repeated twice and the score used here was the average difference in "reading" times between the name and asterisk conditions.

5 and 6. In an experiment in the Sternberg (1970) paradigm Ss were sequentially shown from one to six consonants and then shown a single probe consonant and asked whether the probe was in the previously exposed set. Response time was recorded and, for correctly identified instances, these times linearly regressed on the number of digits in the associated target set. For each S, then, a slope and intercept value were obtained.

7 and 8. Strings of fifteen digits were presented binaurally to Ss with recall cued immediately following presentation. In recall Ss were instructed to recall in order as many digits as possible beginning with the first digit heard. Ten trials were presented with each scored for the number of digits recalled in order. In this analysis two scores were employed--a Digit Span, Final score (average of performances on the last five trials) and a Digit Span, Gain score (difference between the Final average and the average over the first five trials).

9 and 10. In a task patterned after Massaro (1972) four digits and four consonants were presented dichotically, two digits and two consonants to each ear. Following presentation Ss were cued to recall the presented material. On some blocks of trials Ss were to report by ear, i.e., report what they heard to the right ear or the left ear. On other blocks they were asked to report by category, either digits or consonants. While they knew whether they were going to have to recall by category or by ear, which category or which ear was not cued until after the presentation. Two scores were extracted for the present analysis. The Category Score gives the number of items correctly reported over all 40 category trials. An Ear Minus Category Score was obtained by subtracting the category score from a similar score obtained from the ear trials.

11 - 14. A final set of four scores was obtained from a study of clustering in recall of a list of nouns based on the experimental paradigm of Puff (1966). During their first laboratory session Ss were shown item by item, two lists of 30 common nouns. Each list was shown twice with subjects asked for recall immediately following each presentation (four recalls). Each list consisted of ten nouns each from three semantic categories (fruits, occupations, animals, etc.). For half the subjects the list presented first was blocked, all ten members of a given category appearing contiguously, and the list presented second was in pseudo-random order. For the other half of the Ss this order was reversed. When Ss returned for their second day in the laboratory they were asked to recall each of the two lists (two more recalls). A clustering score was computed for each of these six recalled lists. In the present analysis four transformed scores were employed: (1) The clustering immediately following the second presentation of the blocked list

provided a base score, B1; (2) this base clustering minus clustering for second presentation of pseudo-random list, B1-R1; (3) base clustering minus clustering for second day recall of blocked list, B1-B2; and (4) second day blocked clustering minus second day random clustering, B2-R2.

Results

Correlations between the psychometric and laboratory data are shown in Table 1. The response time measures--Motor R T, Choice Time, the Stroop measure, and the two scores from the Sternberg task--correlated negatively with paper and pencil test performance, as might be expected. Proportion of correct responses in the choice reaction time task correlated only weakly, though positively, with the psychometric measures. This laboratory measure had little variability, however, as few errors were made (average proportion correct was .93). The negative correlations involving Digit Span, Gain suggest the possibility that, as improvement on the average was small (from 5.75 digits to 6.23 digits), big gains were registered by those who had not done well in the initial trials. The digit span score itself was not highly correlated with any of the psychometric measures.

The Category Scores from the dichotic listening task correlated positively with nearly all of the paper and pencil tests. Raw ear scores were considerably smaller than category scores (roughly 70 as opposed to 90 on the average). The pattern of correlation for the Ear Minus Category scores suggests that highest psychometric scores were earned by Ss whose category performance far outstripped their ear performance. Finally, the Clustering Score is such that low scores (actually large negative scores) indicate greater clustered recall. Except for the reversal of signs the pattern of correlations for the clustering on immediate recall of the blocked list (B1) is quite similar to that for the Category Score from the dichotic listening task. The difference in clustering scores between the immediate recall of blocked and randomized lists (B1 - R1) was not well correlated with any of the psychometric measures. (Clustering was, of course, greater for the blocked than for the random list.) Clustering for the blocked list was almost exactly the same for delayed as for immediate recall (the score B1 - B2 in the

Table 1

Correlations Between Psychometric and Laboratory Measures

(Decimal points omitted)

	Verbal Comprehension	Numerical Ability	Space Visualiza	Numerical Reasoning	Verbal Reasoning	Clerical, Number	Clerical, Name	Hidden Figures
Motor R T	-40	-38	-42	-40	-27	-17	-38	-27
Choice Time	-40	-45	-55	-50	-30	-28	-37	-40
Pr Corr CRT	21	11	12	04	14	10	14	17
Stroop (Wd-*)	04	-27	-19	-32	-16	-35	-38	-09
Sternberg Slope	-07	-10	-27	-16	-07	-24	-26	03
Sternberg Intercept	-28	-36	-49	-31	-16	-29	-39	-27
Digit Span, Final	-04	02	-03	02	-12	22	16	05
Digit Span, Gain	-10	-26	-24	-21	-29	-06	-17	-07
Category Score, D L	55	46	49	52	32	02	26	48
Ear-Category, D L	-21	-29	-23	-31	-18	-16	-29	-25
Clustering, B1	-52	-48	-48	-61	-47	-02	-37	-34
B1-R1	06	10	10	-07	07	00	09	-14
B1-B2	-12	-22	-21	-28	-25	01	-03	-35
B2-R2	-18	00	06	04	05	06	00	20

tat'e had a mean close to zero). This difference, however, did correlate with a number of psychometric measures. Increased reliance on semantic clustering between immediate and delayed recall tended to be negatively related to certain paper and pencil test performances. The last measure included in Table 1, B2 - R2, the difference in clustering of delayed recall between the blocked and randomized lists had near zero correlations with the psychometric measures. (For the randomized list, however, clustering was considerably greater on the average for delayed than for immediate recall.)

Table 1 reports the zero order correlations between laboratory and psychometric measures. Because many laboratory measures are themselves not pure measures of information processing parameters--for example, clustering score B1 may be interpreted as a measure of short-term serial recall ability as well as any semantic clustering tendency--these correlations are more equivocal than we would like. The laboratory performances were correlated among themselves. This is reflected in Table 2. The quickness of response measures--1, 2, 4, 5, and 6--tended to be positively correlated. Clustering on immediate recall of a blocked list had a sizeable negative correlation (-55) with the category score in the dichotic listening task. Tables 1 and 2 provide the essential data for the generation of the results we would like to report.

What we are attempting to explore in these systematic stepwise multiple regression analyses is a quantitative analog to Carroll's (1974) point about the information processing or memorial complexity of most paper and pencil tests. Our strategy was to order the laboratory measures by level of complexity ranging from the motor reaction time measure, which places the least load on memorial operations, to recall measures in the dichotic listening and clustering studies. Then, we asked of the data how much of the inter-individual variability in performance on each of the paper and pencil tests could be accounted for successively by the independent contributions of the several laboratory measures, working up from the least complex. The results are in Table 3. Entries in the columns headed R^2 are cumulative proportions of variance accounted for. Motor Reaction Time accounted for 16% of the variance in the Verbal Comprehension scores; Motor Reaction Time plus Choice Time accounted for 22% of

Table 2

Intercorrelations among Laboratory Measures

(Decimal points omitted)

	2	3	4	5	6	7	8	9	10	11	12	13	14
1. Motor R T	47	-07	21	42	69	00	15	-52	38	36	-28	09	-19
2. Choice Time		14	27	43	55	-21	-11	-40	30	30	03	04	07
3. Pr Corr CRT			14	25	12	-29	-41	08	06	-20	17	-19	16
4. Stroop (Wd-*)				27	21	-32	16	-11	22	14	-02	-07	-15
5. Sternberg Slope					39	-17	-11	-21	17	15	-44	-21	05
6. Sternberg Intercept						-21	-07	-45	44	21	-13	-02	-06
7. Digit Span, Final							65	-04	-02	14	-19	24	-28
8. Digit Span, Gain								-12	02	34	-17	32	-25
9. Category Score, D L									-75	-55	04	-35	02
10. Ear-Category										32	08	26	02
11. Clustering B1											16	54	09
12. B1-R1												28	32
13. B1-B2													-32
14. B2-R2													

Table 3

Predicting Psychometric Performance from Laboratory Measures:

Increments to the Squared Multiple Correlation

(Decimal points omitted)

	Verbal Comprehension		Numerical Ability		Space Visualiza		Numerical Reasoning		Verbal Reasoning		Clerical, Number		Clerical, Name		Hidden Figures		
	R^2	Δ	R^2	Δ	R^2	Δ	R^2	Δ	R^2	Δ	R^2	Δ	R^2	Δ	R^2	Δ	
Motor R T	16	16	15	15	18	18	16	16	07	07	03	03	15	15	08	08	A
Choice Time	22	06	25	10	34	16	28	12	11	04	08	05	20	05	17	09	
Stroop (Wd-*)	25	03	27	02	34	00	31	03	12	01	16	08	27	07	17	00	
Sternberg Intercept	26	01	27	00	36	02	32	01	13	01	19	03	28	01	17	00	
Sternberg Slope	29	03	30	03	36	00	34	02	14	01	20	01	28	00	24	07	B
Pr Corr CRT	32	03	32	02	40	04	34	00	16	02	25	05	33	05	27	03	C
Digit Span, Final	32	00	32	00	42	02	35	01	18	02	26	01	33	00	27	00	
Digit Span, Gain	32	00	38	06	46	04	37	02	21	03	27	01	35	02	27	00	D
Category Score, D L	43	11	43	05	49	03	45	08	23	02	29	02	35	00	37	10	
Ear-Category, D L	49	06	44	01	54	05	47	02	23	00	32	03	37	02	39	02	E
Clustering, B1	53	04	46	02	55	01	55	08	29	06	32	00	41	04	39	00	F
Clustering, B1-R1	55	02	50	04	55	00	55	00	31	02	33	01	42	01	40	01	
B1-B2	59	04	50	00	55	00	55	00	31	00	34	01	43	01	43	03	
B2-R2	60	01	50	00	55	00	56	01	31	00	34	00	43	00	47	04	G

the variance, etc. The delta entries are the increments, the additional proportion of variance accounted for. It is important to keep in mind that these increments are for partial variables. The contribution of the Choice Time variable, for example, is the contribution of that measure after it has had partialled from it the influence of Motor Reaction Time.

Figure 1 is a simplication of the data in Table 3. The measures have been grouped as shown by the letters along the right edge of Table 3. Thus, A indicates the variance accounted for by the Motor Reaction Time; B is a measure of the amount of additional variance accounted for by the remaining response time measures; C is the contribution of a carefulness-of-response measure--proportion of correct responses in the simple, two-choice reaction time study; D carries the incremental contribution of the digit span study; E does the same for the dichotic listening task, and F and G bring in, finally, any remaining contribution of the clustering on recall scores.

Discussion

What can we say about these results? Before looking at each of the test entries in Figure 1 and at Carroll's characterization of what is important to doing well on them, let us note one potentially confounding factor. As Carroll (1974) properly noted, the time limit on a test introduces a speed component to test scores of some magnitude. Because Carroll addressed himself to the question of what is important in responding to an item rather than to a speeded test as a whole, we might expect that a generalized measure of response time would be a more significant determiner of total test performance than of success with a single item. That is, the component labelled "A" in Figure 1 may be inflated.

Space Visualization. Carroll characterized Factor Vz as dependent on a process occurring in STM whereby a spatial representation is "mentally" transformed. This process is assumed to produce both capacity and rate differences between individuals. We have nothing in the laboratory measures that speak to the question of capacity for spatial representation. However, the rate at which this representation can be manipulated could well be not a unique rate but one dependent upon more general STM processing rates, based upon the appreciable individual differences accounted for by the time components A and B.

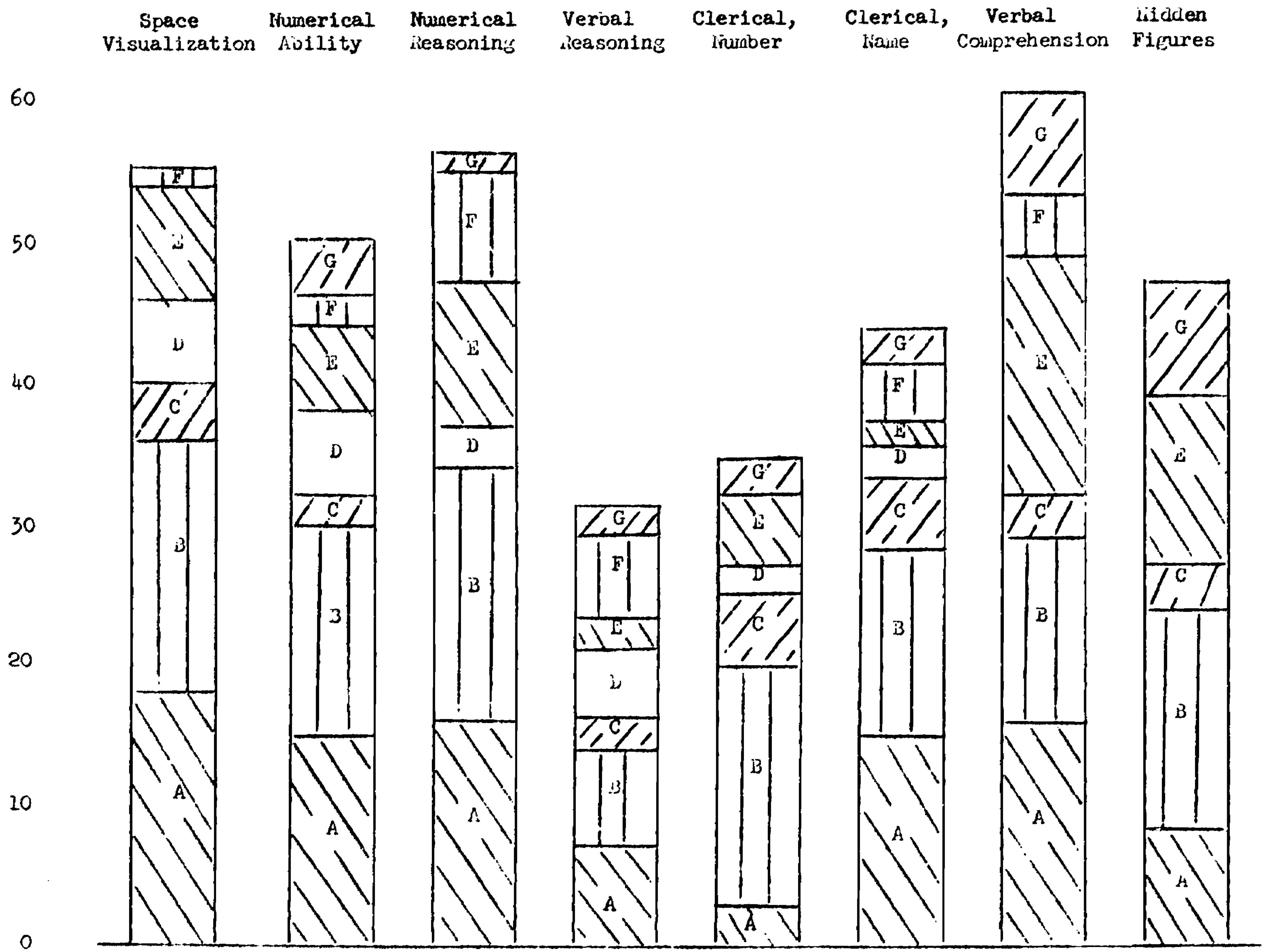

Figure 1. Cumulative Proportion of Variance Accounted For (see Table 3 for explanation of laboratory measures).

Numerical Ability. Factor N requires retrieving number associations and arithmetic algorithms from LTM and performing serial operations on the stimulus materials using the retrieved algorithm. Individual differences, Carroll noted, appear in both content and temporal aspects of the retrieval and manipulative operations. Carroll also felt that special strategies, chunking numbers, for example, may also contribute to individual differences. It would be nice to be able to assert that all high school juniors know how to perform these arithmetic tasks, that they all have the requisite store of algorithms in LTM. It may be overly optimistic, however, to do so. Rate, either of retrieval of an algorithm and/or of application of the algorithm is important and could well be determined by the general processing rates that are assessed in A and B.

Numerical Reasoning. The number series problems were most akin to Factor I, Induction, suggested by Carroll to require searching a general logic store in LTM for relevant hypotheses. The major determiner of success is whether the contents hold the solution. Some subjects, however, might construct new hypotheses by serially operating upon STM contents. A substantial amount of the variability in this test is accounted for with no knowledge of the contents of an LTM logic store. Perhaps the range of inductive hypotheses likely to be employed is limited enough by the problems and subject sampling to not be a source of individual differences. The importance of speed, again, plus the relatively heavy contribution of the dichotic listening and clustering scores suggests that operations on STM were indeed contributory to success.

Verbal Reasoning. Representative of Factor Rs, Syllogistic Reasoning, this test would require by Carroll's analysis retrieval of meanings and algorithms from LTM and the performance of serial operations in STM on the retrieved materials. Individual differences in content and temporal aspects of performance are postulated. There is some likelihood, as well, that Ss vary in attention paid to details of the stimulus material. Results for Verbal Reasoning are in interesting contrast to those for Numerical Reasoning. That only a relatively small proportion of the total variance was accounted for, together with a depressed contribution of the processing rate measures, suggests that indeed it is

individual variability in the contents of some LTM store (rather than the speed with which it can be accessed) that accounted for individual differences in performance. An alternative explanation would be individual variability in performing transformations of statements prior to evaluating their logical consistency. If E, F, and G measure a general class of such transformations, then their small contributions to Verbal Reasoning argue against this alternative. Finally, if C, the contribution of carefulness-of-response is interpreted as "attention to detail" (appealing in connection with the next two tests), then "attention to detail" was not an important source of variability in Verbal Reasoning.

Clerical, Number and Name. Both subtests tap Factor P, Perceptual Speed, which should be primarily sensitive to the temporal parameters of a visual search through a field for specified elements. This search, Carroll posited, occurs by addressing sensory buffers. Failure to account for more of the variance in these two tests cannot be laid to failure to tap some LTM store. It is, in fact, puzzling that there is so much left unaccounted for. The inference is that the speed of processing required in clerical work is not well explained by the speed of processing measures tapped by A and B. That C makes its greatest contribution here is suggestive of important individual differences in some kind of testing or checking loop.

Verbal Comprehension. This test and Factor V of the same name are synonymous with what in everyday parlance is vocabulary and Carroll has written that performance is almost exclusively dependent upon the contents of a lexicosemantic LTM store, upon the probability that S can retrieve the correct meaning of a word. What we see in Figure 1 is, of course, the same thing that we have found in our earlier studies, that one can account to a very large extent for differences in verbal ability without ever inquiring about what Ss may know about the language. I hasten to add, however, that being able to account for the variability in vocabulary of a group of adolescent native English speakers may not meet the same goal as knowing what an individual S's vocabulary is. The Vocabulary test example, however, draws rather nicely a distinction (notice I do not say the distinction) between aptitude and achievement measures.

The size of one's vocabulary is one measure of that individual's achievement. That it is so predictable from measures which are, from an information processing point of view, more basic than inventorying the contents of an LTM store suggests that vocabulary could be supplanted as an aptitude measure, however.

Hidden Figures. This last test is a measure of Factor Cf, Flexibility of Closure, and involves, by Carroll's analysis, an STM process whereby a figure is imaged in relation to a surrounding visual-representational field. Both capacity and temporal aspects may be involved. The test was, for our sample, a very difficult one--the average score was 3.5 out of a possible 16. This is reflected in the relatively small contribution of the motor reaction time measure--so few responses were made by the average S that speed of making the response was unimportant. Choice Time was important, as it was for the Spatial Visualization and Numerical Reasoning tasks, suggesting that successful test performance requires rapid evaluation of alternatives. Because of the purely figural nature of the stimulus material it is interesting to note the rather large contributions of E and G, measures which are grounded in symbolic and semantic manipulations. The suggestion here is that the ability to effect these manipulations is not independent of the ability to manipulate figural material.

Despite the shortcomings of the available data these analyses suggest that Carroll's thoughtful analysis of the demands psychometric tests place on human beings as information processors can be fruitfully linked to laboratory measures to gain better understanding of what the psychometrists call intelligence and what the experimental psychologist calls cognition. If we were to hazard predictions as to the outcome of such work they would be two: First, the distinction between assessing individual differences in the contents of LTM stores and assessing individual differences in abilities to manipulate information (including storage and retrieval from LTM) will be much better understood. Second, as a result of this, the number of parameters relating to such abilities will be far fewer than the number of factors--mixtures of information manipulation abilities, strategies, and LTM stores--that present day psychometrists must deal with.

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